RESULTS OF THE AFWL/LLNL SSVCO EXPERIMENTS*

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In cooperation with AFWL, we have conducted a series of tests of the SSVCO powered by the TEMPO Bleumlein. A matrix of anode-anode gaps and of anode-cathode gaps were tested. For three of the AA gaps, the performance would peak as the AK gap was varied. The RF power was measured with a single cluster antenna located in an anechoic chamber. The peak power achieved was in excess of 1 gW and the peak instantaneous efficiencies ranged from 5 to 20% for the optimum geometries. We have found that optimum efficiency conditions correspond to beam frequency equals reflex frequency equals measured frequency and wavelength equals beam diameter.

Introduction

Experiments on the Side shooting Virtual Cathode Oscillator (SSVCO) have shown that the device is capable of producing RF power with an efficiency in excess of 10%. Conditions necessary for the high efficiency are those for which the beam frequency is equal to an integral multiple of the reflex frequency. Our interpretation is that under these circumstances the charge sheets will collide with the greatest velocity and achieve the greatest acceleration during the collision process. The strong acceleration associated with the reflection of the charge sheets produces the microwave radiation. An additional condition on high efficiency is that the wavelength of the emitted RF radiation equals the beam diameter for a planar beam. The processes involved and the relevant equations have been discussed previously.

For the present purpose it is sufficient to note that the reflex frequency is a function of the velocity of the charge sheets and the distance traveled between the cathode plasma emission surface and the point of reflection at the virtual cathode. This distance is the sum of twice the actual anode-cathode (AK) gap and the space between the anode screens (the AA gap). The actual AK gap is the geometrical AK gap reduced by the growth of the cathode plasma. For most of our data, the plasma closure velocity v_p is $2 * 10^6$ cm/sec. The reflex frequency f_r is approximated by the relation

$$f_r = \frac{1.46 * 10 \quad V/C}{2\,(d_{ak} - v_p t) + d_{aa}} , \quad \text{(MKS)}$$

where the coefficient has been obtained experimentally. The time from the initiation of the current pulse is t. V/C is the electron velocity corresponding to the acceleration voltage and normalized to the speed of light. The distances d_{ak} and d_{aa} correspond to the geometrical AK and AA gaps, respectively.

The beam frequency, also known as the virtual cathode frequency, is computed from the density of the electron beam. An approximate relation, obtained by dividing the beam current density by the beam velocity corresponding to the acceleration voltage and multiplying by an experimentally obtained constant, is given by

$$f_{bo} = 2.4*10^6\{j/(\gamma^2-1)^{1/2}\}^{1/2} \quad \text{(MKS)}$$

with j = current density.

The research on the SSVCO has also shown that it is possible to extend the RF pulse length beyond that normally observed with VCOs. It is typical of VCO operation that the RF pulse terminates well prior to the power input pulse. Our interpretation of this phenomenon is that the RF pulse is terminated as a consequence of positive ions accumulating in the virtual cathode region, thus lessening the net space charge and destroying the reflex mechanism. We have found that this accumulation can be greatly reduced by cleaning the anode of surface contaminants. This is done by firing a beam pulse, driving the impurities off the electrodes, and collecting the impurities on a fast pumping surface such as one cooled by liquid nitrogen. The SSVCO RF pulse duration has been extended from 70 ns to 250 ns in experiments at LLNL by following this procedure.

The power level at which the LLNL SSVCO experiments have been conducted have been limited by a poor match of the SSVCO impedance to that of the Marx power supply. The supply is sufficiently inductive that the cathode current ramps up in time; the frequencies therefore change with time and currents on the order of 10 kA are obtained only at the end of the pulse. Operation of the SSVCO on TEMPO was of interest since it would allow experiments at greater input power, though at shorter pulse duration of approximately 150 ns. The rise time of the pulse was 50 to 70 ns, so the steady state operation required to remain in resonance was not possible, and sustained operation at high efficiency was not expected.

Experimental Arrangement

A velvet cathode produces a 4.35 cm radius solid electron beam constrained by an imposed axial magnetic field of approximately 3 kg. The AK spacing was varied from 1 to 3 cm. The anode consisted of a double screen; the spacing between the screens could be varied. The variation employed for these tests ranged from 0 to 1.4 cm. The screens were constructed of 316, 4 mil stainless steel with a spacing of 10 wires/inch. The drift space from the second anode screen to the collector was approximately 15 cm. The radiation created by the oscillations of the beam charges flows out radially through an azimuthally symmetric window located between the magnets.

The radiation flows into an anechoic chamber consisting of two parallel conducting plates with the same spacing as the window section between the magnets, 25 cm. Within an azimuthal angle of ~ 40 degrees the radius of the chamber extends to approximately 250 cm. The remaining section of the chamber is shorter, on the order of 100 cm. The parallel plates are terminated at their extremity by absorber backed by a conducting sheet. The long section of the anechoic chamber contains the diagnostics. For the tests described here, the diagnostics consisted of one cluster antenna. The cluster antenna consists of an orthogonal

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set of short (1 cm) dipoles. The power from the three channels is summed and forms the output of the cluster antenna. This output is a quantity that is proportional to the incident radiation power density and nearly independent of the polarization and angle of the Poynting flux.

Test Procedure

The purpose of the test was to measure the RF power and the input current and voltage as a function of the diode geometry in the range provided by the TEMPO power supply. The data serves to extend the LLNL data base on the conditions for which high power can be generated through the resonance process.

The TEMPO facility has the outstanding feature that the cathode can be moved on a shot-to-shot basis without an air cycle. Changing the AA gap did require an air cycle. We decided to obtain data for a matrix of AK and AA spacings which would include geometries for which, on the basis of LLNL data, we would expect to find resonant, high efficiency operation. The geometries were

AK = 1.0 cm to 3.0 cm in 0.25 cm steps, and
AA = 0 cm, 0.5 cm, 0.75 cm, and 1.4 cm

Data was obtained for most of these points. The data consisted of current and voltage data, RF data for the cluster antenna, a heterodyne measurement of the RF frequency, and the attenuation in the various recording channels.

The SSVCO will occasionally malfunction. The most frequent malfunctions are due to the beam burning a hole through the screen, and/or generation of a non-planar beam, either filamentary or annular. The impedance of the source provides information on the function of the device. Specifically, the ration of the Child-Langmuir current to the measured cathode current is an excellent measure of the condition of the cathode and the emitted electron beam. The computed current must include the effect of plasma closure.

Test Results

The data was recorded on scope pictures. Data reduction was done in two ways: the data was read for all shots from the pictures at times of approximately 90, 120, and 150 ns after the initiation of the current pulse, and, for some shots, the data was digitized from the photos. Where single data points are presented, they have been read at the indicated times. In order to get a sense of the behavior of the data during the geometry scans, the raw data at 120 ns is presented in Fig. 1 for one of the four AA dimensions. The only correction included is a x4 attenuation change for some of the high power shots. The effect of the non-linearity of the diodes, the difference between them, and the effect of frequency on the cable attenuation and the power received by the antenna elements has not been included. The data appears to be fairly reproducible, with the output signal increasing and diminishing in a regular fashion as the AK gap is varied.

The efficiency of the RF production of the SSVCO for the four AA gap geometries is shown in Fig. 2. The efficiency was calculated using the previously obtained antenna calibration and the measured attenuation of all the RF cables as a function of frequency. The non-linearity of the diodes was not included, so the computed RF power is less than the actual RF power for the high power data points. The inductive voltage generated along the cathode stem has not been included in the power calculations, so the powers and efficiencies at 150 ns are high by an estimated maximum of 25%.

As is seen from Fig. 2, the power and efficiency emitted by the SSVCO is a strong function of electrode geometry. In three of the data sets, for AA = 0, 0.5, 0.75 cm, variation of the AK gap caused the RF power to peak. The peak power, for AA = 0.75, exceeds 1 GW and the peak efficiency, including the above correction, is in the 10-20% range. For AA gaps of 0.0 and 0.5 cm, the power peaks at lower values and the peak efficiencies are between 5 and 10%, still respectable. The data scan for AA = 1.4 cm was terminated at an AK gap of 1.5 cm due to a failure of the anode screen. The power is low for the 1.5 to 3 cm range of AK gaps for which data was obtained. The data shown in Fig. 2 is taken at approximately 90, 120, and 150 ns after the onset of the cathode current. The RF power produced tends to be greater at the later times, thus contributing to the spread in the data shown. Examination of a number of digitized shots, not shown here, indicates that the RF output is terminated as a consequence of the termination of the input power pulse rather than as a consequence of ion neutralization.

The reflex frequency appears to be a good measure of the emitted frequency for the 3 GHz range of primary interest. The measured frequency is strongly correlated with the reflex frequency, with a best fit being

$$f = 2.2 + 0.23*f_r$$

with the frequencies in GHz. A heterodyne method was employed to measure the emitted frequency, hence the frequency was only obtained at one time during the shot, and not for all shots. Since the calibration factors are functions of frequency, the power for all data points was computed using the above fit to the measured frequency.

We have been able to show that only under a very restricted conditions is high efficiency operation obtained. The LLNL database has been analyzed in detail and it shows that in order to achieve high efficiency with a planar vircator several conditions must apply. These are

$$f_r = f_b = f_m, \text{ and}$$
$$\lambda = D ,$$

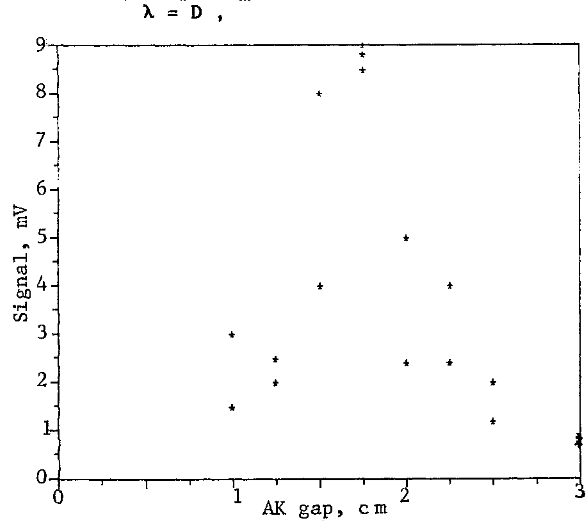

Figure 1. The unprocessed antenna signal at 120 ns after the initiation of the cathode current for different AK gaps, AA gap = 0.5 cm, illustrates the regularity of the signal variations with AK gap.

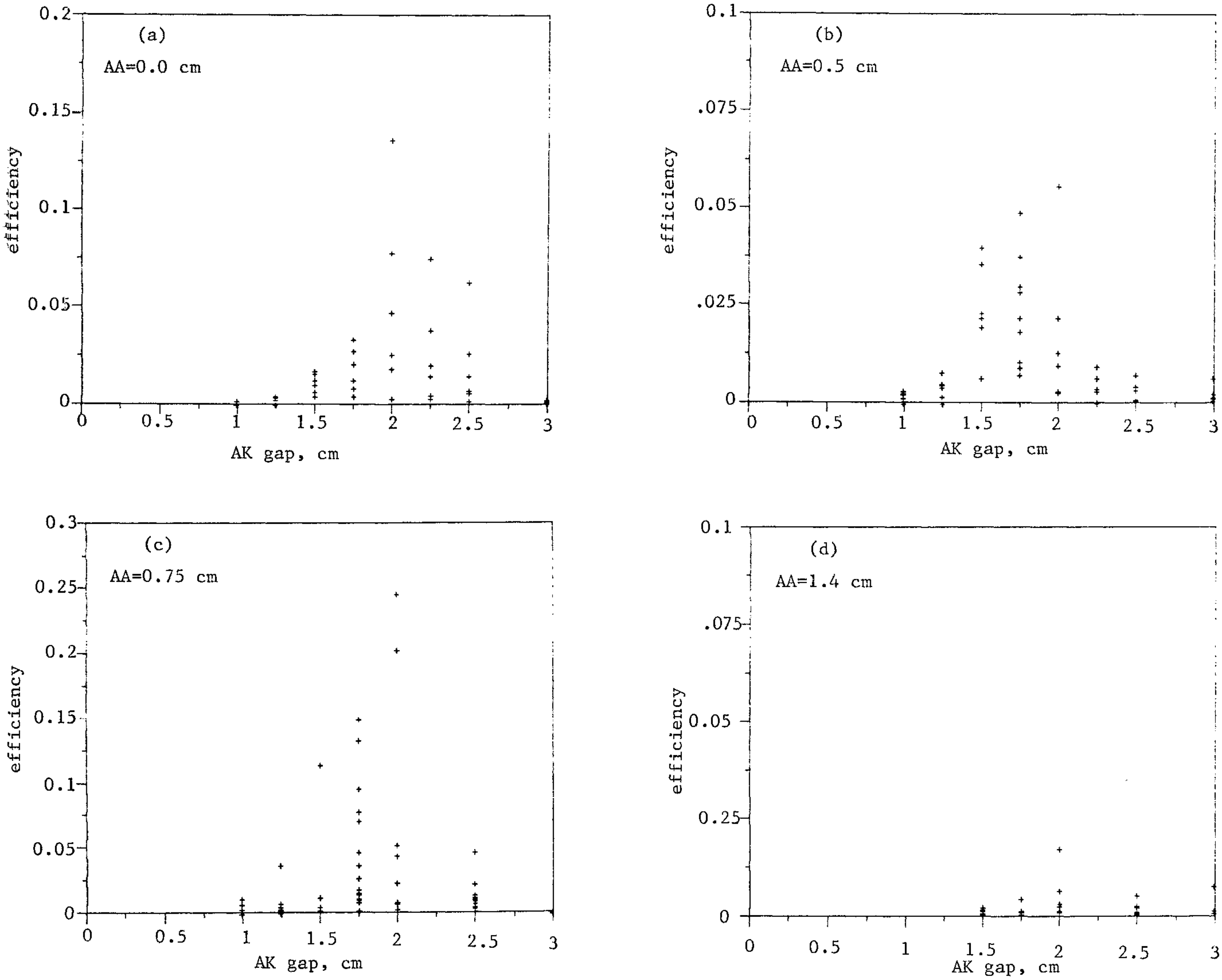

Figure 2. The instantaneous RF production efficiency at all times sampled for a range of AK gaps from 1 to 3 cm: a) AA gap = 0 cm, b) AA gap = 0.5 cm, c) AA gap = 0.75 cm, d) AA gap = 1.4 cm; note the different vertical scales

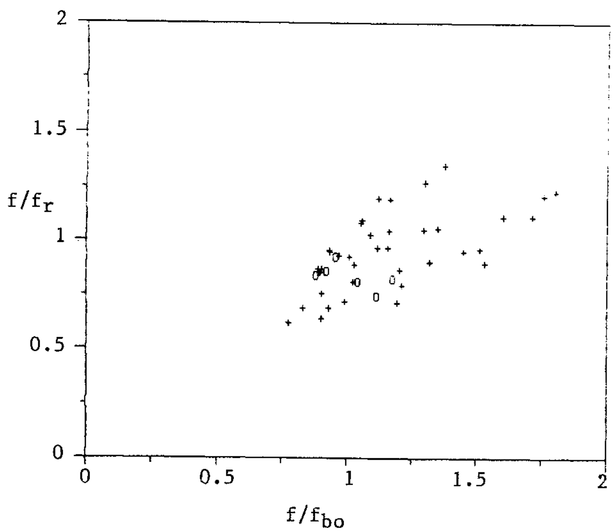

Figure 3. A plot of the frequency ratios f/f_r and f/f_{bo} for data taken at 120 ns shows that the high efficiency points (o) are localized at frequency ratios near unity, indicating that $f_r = f_{bo} = f_m$ at high efficiency. The beam diameter = wavelength for these points. f is the fit to the measured frequency.

where D is the cathode diameter and λ the wavelength of the emitted radiation. In addition, the cathode current should be no less than approximately one half of the Child-Langmuir current of the diode, computed with the proper closure velocities. Fig. 3 shows that these relations hold for this experiment as they do for the larger LLNL database obtained at lower diode power. The efficiency peaks at 3 GHz, in agreement with the wavelength condition. The complete results of the analysis of the LLNL database will be published elsewhere.

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Future Work

We have found several operating conditions for which the SSVCO will produce radiation with efficiency in excess of 10%. Though this result is a step forward toward producing a useful device capable of large energy output, it is clear that steady state operation of the diode is required to maintain the resonance conditions. We are presently investigating cathodes capable of providing those conditions. We have also shown that the RF output power and efficiency increases with increasing magnetic field for the SSVCO[3]. It appears possible, therefore, that with careful design and operation, a magnetized and resonant virtual cathode oscillator will be an efficient source of narrow band radiation at high power and energy.